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595

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FROM THE SMITHSONIAN REPORT FOR 1875.

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As ordinarily received by the ear, sound may be considered as an aërial impulse or succession of impulses radiating in all directions from the origin of disturbance, and consisting *in the main* of a small to-and-fro movement generating an expanding wave of compression of determinate velocity, necessarily followed by a corresponding wave of attenuation. This vibration is a mass-movement of the air, and not a molecular movement; and the surface or surfaces of similar phase of movement are equidistant from the origin; or, in other words, the wave-fronts are essentially spherical.

The transmission of sound through liquid and solid mediums, though similar in character, and subject to similar perturbations, will not here be considered.

Sound, while differing widely from light in the character of its waves and their order of magnitude, yet thus moves like light in radial lines, and like light is diverted from its rectilinear course whenever its waves undergo an *unequal* retardation or acceleration; that is, whenever any segment of a series of advancing wave-fronts (regarded as an acoustic beam) receives from any cause an unequal velocity on its opposite sides, such beam is bent toward the side of least velocity, and from the side of greatest velocity; the line of impulse or of acoustic effect being always perpendicular to the surface of the wave front.

By sound-beams, or sound-rays, the longitudinal direction of sound is to be understood; by sound-waves, the transverse surfaces of simultaneous movement are to be understood. The amplitude of the wave-motion is very minute, being ordinarily a barely visible magnitude. It lies in the direction of the wave-length, or of the sound-ray. In the case of light, the amplitude of vibration is transverse to the wave-length, or to the direction of the ray.

If we imagine a symmetrical boat on a perfectly still sea or lake, mechanically propelled by oars of precisely similar character and movement, it is obvious that such a boat must advance in a perfectly straight course. If placed in a uniform current, the boat, though drifting with the current, would still maintain a rectilinear path. If, however, such moving boat were to *enter* a current, or to encounter a difference of current on its opposite sides, or were it to encounter water of different density, as by passing *obliquely* from salt-water into a margin of fresh water, then, *at the moment of transition*, the oars meeting with unequal

resistances, the course of the boat would be changed, or "refracted." This image may be taken as a rough illustration of the phenomenon of "refraction" generally.

There are three different methods in which sound-waves passing through a gaseous medium may suffer such unequal disturbance of velocity: first, by variations of *density* in the medium, sound moving more slowly through a dense air than a rare one, the pressure being the same; second, by variations of *elasticity* in the medium, sound moving more swiftly with increase of elasticity, the density being the same; and, third, by variations of motion or *current* in the medium, sound traveling by convection faster with the wind by a small percentage, according to its velocity, and more slowly against the wind.*

There is no doubt that light also would be subject to all three of these forms of refraction, as its velocity is necessarily retarded by an increase of density in the medium, by a reduction of the elasticity of the medium, and by an adverse motion of the medium.

A fourth cause of velocity disturbance in the case of sound is found in the *temperature* of the medium, sound moving more swiftly in a heated atmosphere than in a cooler one. This cause of acoustic refraction is practically a highly important one; though it may be theoretically resolved into one of the preceding conditions, since the only dynamic effect of heat on a gas is to increase its elasticity if the volume be constant by confinement, or to increase its volume if unconfined without changing its elasticity.

The relation of these atmospheric conditions to each other is exceedingly simple.

The *density* of a perfect gas (the inverse of its volume) varies directly as the pressure, the temperature being constant, or inversely as the absolute temperature, the pressure being constant.

The *elasticity* of a perfect gas varies directly as the pressure, the density being constant, or inversely as the density, the pressure being constant. It also varies directly as the absolute temperature, the volume being constant.†

From these relations it follows that increase of atmospheric pressure does not affect the velocity of sound; for although the *density* is directly proportional to the pressure, and this diminishes the velocity, yet as the *elasticity* is also directly proportional to the pressure, and this increases the velocity by precisely the same amount, the two effects are neutralized.

* The ratio of the velocity of the wind to that of sound (one or two per cent.) is too small to be of any account *directly*. Differentially, it becomes very important. A uniform wind has no practical effect on sound except to slightly flatten or lower the pitch in its own direction, and to sharpen or raise the pitch in the opposite direction.

† According to Waterston, "when air is compressed or dilated, the absolute temperature varies as the cube root of the density, and the tension as the fourth power of the absolute temperature, or cube root of the fourth power of the density," (*Rep. Brit. Assoc.*, 1853, p. 12 of Abstracts.) This would indicate a striking departure from the condition of a perfect gas.

We have as the laws of sound-motion in a perfect gas:

1st. Its velocity is directly proportional to the square root of the elasticity of the air.

2d. Its velocity is inversely proportional to the square root of the density of the air.

3d. Its velocity is directly proportional to the square root of the absolute temperature of the air.

The theoretical case of unequal elasticity of the medium, presenting no practical examples, excepting in the passage of sound from water into air obliquely, or from air into water, may be here neglected; and the remaining actual conditions of acoustic refraction are limited to three, viz: those of density-inequality, wind-inequality, and temperature-inequality. It is important to observe that the two fundamental principles underlying the discussion of acoustic refraction of whatever origin are, first, that the directions of progressive impulse are always at right angles to the surface of the wave-front, and, secondly, that any deformation of the spherical surface of the wave-front must accordingly deflect the line of acoustic propagation from its original radial direction.

1.—REFRACTION FROM INEQUALITY OF DENSITY.

In 1852, Mr. Carl Sondhauss was the first to demonstrate acoustic refraction, and he exhibited it by means of a lens of carbonic-acid gas.

It may be here premised that, in accordance with the previous summary, *hydrogen*, having at the pressure of the atmosphere the same elasticity, should, from this circumstance alone, transmit sound with the same velocity as ordinary air; but as its rarity is fourteen times greater, the velocity of sound in this medium is increased nearly four times, so that while at ordinary temperature (65° F.) sound in air would move over 1,125 feet in a second, or one mile in 4.7 seconds, it would move over 4,250 feet per second (or one mile in 1¼ second) in an atmosphere of hydrogen. On the other hand, as *carbonic acid*, at the same pressure and with nearly the same elasticity, has a density rather more than 50 per cent. greater than air, it would retard the velocity of sound about one-fifth, or reduce it to 912 feet per second, or one mile in 5.7 seconds.

Mr. Sondhauss first employed a thin membranous balloon formed of gold-beaters' skin, but obtained more decided results by forming the envelope of a double convex lens with two spherical segments of collodion film, attached to a leaden hoop, in which were suitable openings for the introduction of the gas. The ticking of a watch placed at some distance behind such lens was heard most distinctly at a focal point in front of the lens.

"In order to arrive at a more certain decision, the experiment was arranged in such manner that while the observer sat at the other side of the lens with closed eyes and listened for the ticking of the watch, the lens was alternately removed and again brought into position, whereby it was shown that the ticking of the watch disappeared every

time upon the removal of the lens and was immediately audible again when the lens was replaced between the watch and the ear."—(*Poggendorff's Annalen*, 1852, lxxxv, 381, translated and republished in the *Phil. Mag.* February, 1853, v, 75.)

The accompanying Fig. 1, representing a vertical section of the gas

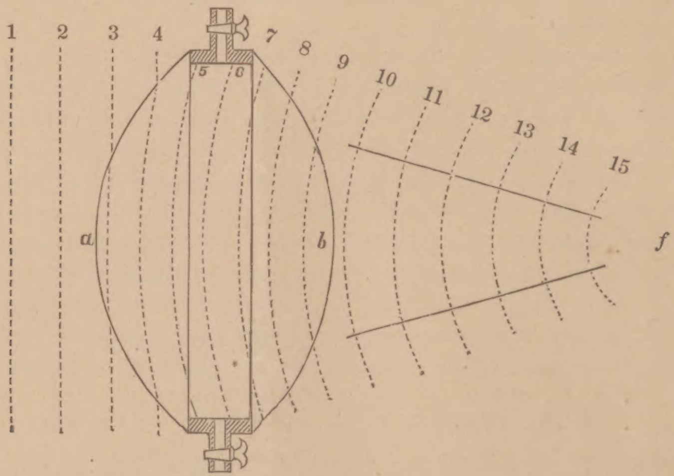

FIG. 1.—Carbonic-acid lens.

lens through its center, will serve to give a more definite idea of the action it exercises on the sound-waves passing through it. For any small area, the wave-front, at some distance from its origin, may be considered as practically a plane surface, and 1, 2, 3, &c., (Fig. 1,) may represent the successive positions of a single advancing wave-front. On entering the convex surface of the carbonic-acid lens at its central point *a*, the wave-face is at once retarded, and successive annuli of the wave passing the surface at increasing degrees of obliquity, the form of the wave-front becomes concave, as shown at 3 and 4, advancing concentrically according to the law of normal impacts, with a uniform though retarded velocity, as shown at 4, 5, 6, 7, &c. On emerging first from the outer margin of the reversed convex surface *b*, the wave-front is accelerated in passing into the common air, and meeting the boundary of the same obliquely becomes still more concave, as shown at 8, 9, 10, &c. Advancing concentrically, its impulses converge with uniform velocity, but increasing energy, toward a focal point, *f*.

It is obvious that if this convex envelope were filled with hydrogen, the action would be just reversed, as shown in Fig. 2. The wave of sound, on entering the convex surface *c*, would be accelerated (commencing at the middle) so as to acquire a continuously convex front, as shown at 5, 6, &c. Passing through the second surface, *d*, and being retarded in a reverse order, the wave-front would advance with an increased convexity, as seen at 8, 9, 10, &c., giving a general divergence of the sound-rays, the focus being negative.

It follows that to obtain a focal convergence by means of a hydrogen lens, we should have to employ a concave form, as shown in Fig. 3. In

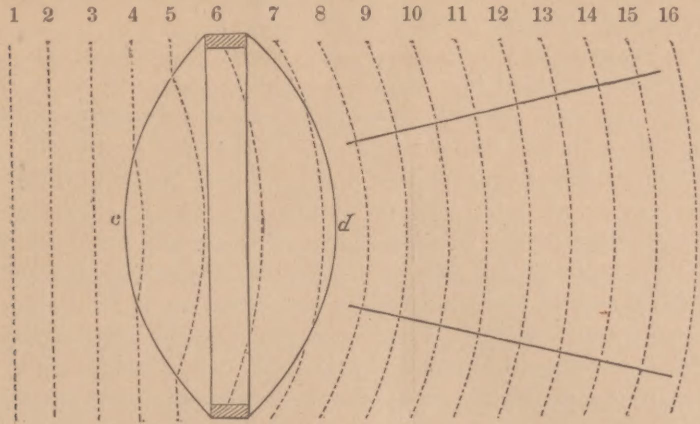

FIG. 2.—Hydrogen lens. (*a*.)

this case, the outer annulus of the wave on entering the projecting surface of the lens *g*, as at 4 and 5, would be hurried forward into a concave form, as shown at 5 and 6, having a general center of convergence at about *e*. On emerging from the second surface, *h*, (supposed here to

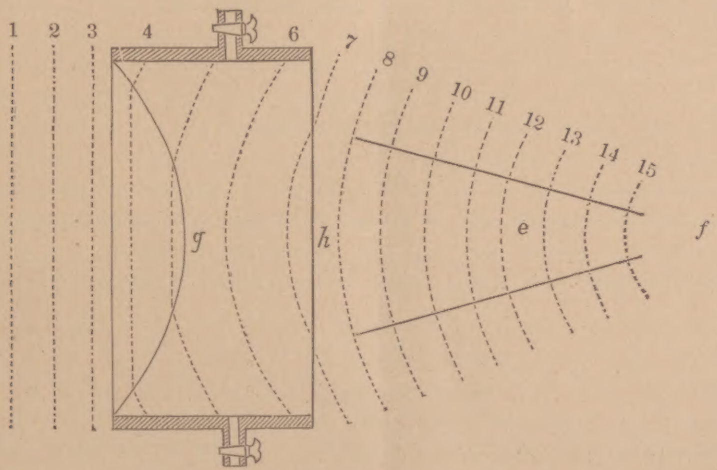

FIG. 3.—Hydrogen lens, (*b*.)

be a plane,) the wave, by oblique retardation, as shown at 7, would be somewhat flattened, as at 8, 9, 10, &c., extending the focal point of convergence to *f*. The effect of a double concave surface to the lens would be to shorten the focal distance according to the degree of concavity.

2.—REFRACTION FROM INEQUALITY OF WIND.

In 1857, Prof. G. G. Stokes showed that differences of motion in the air must exert a bending influence on the beams of sound, and that this

deflection presented the only satisfactory explanation of the familiar fact of observation that sound is usually heard many times farther in the direction of a wind than in a direction opposed to its action. His explanation of this phenomenon is as follows:

"If we imagine the whole mass of air in the neighbourhood of the source of disturbance divided into horizontal strata, these strata do not all move with the same velocity. The lower strata are retarded by friction against the earth, and by various obstacles they meet with; the upper by friction against the lower, and so on. Hence the velocity increases from the ground upward, conformably with observation. This difference of velocity disturbs the spherical form of the sound-wave, tending to make it somewhat of the form of an ellipsoid, the section of which, by a vertical diametrical plane parallel to the direction of the wind, is an ellipse meeting the ground at an obtuse angle on the side toward which the wind is blowing, and an acute angle on the opposite side. Now sound tends to propagate itself in a direction perpendicular to the sound-wave; and if a portion of the wave is intercepted by an obstacle of large size, the space behind is left in a sort of sound-shadow, and the only sound there heard is what diverges from the general wave after passing the obstacle. Hence, near the earth, in a direction contrary to the wind, the sound continually tends to be propagated upward, and consequently there is a continual tendency for an observer in that direction to be left in a sort of sound-shadow. Hence, at a sufficient distance, the sound ought to be very much enfeebled; but near the source of disturbance this cause has not yet had time to operate, and therefore the wind produces no sensible effect, except what arises from the augmentation in the radius of the sound-wave, and this is too small to be perceptible. In the contrary direction—that is, in the direction toward which the wind is blowing—the sound tends to propagate itself downward, and to be reflected from the surface of the earth; and both the direct and reflected waves contribute to the effect perceived."—(*Rep. Brit. Assoc.*, 1857, xxvii, p. 23 of Abstracts.)

FIG. 4.—Ventral refraction.

This action may be illustrated by Fig. 4, in which the larger arrow

above indicates the direction and force of the wind, and the two smaller arrows below the diminished force of the wind in the same direction, by reason of the increasing resistance and retardation toward the surface of the earth. The result is a flattening of the waves at the left side and a swaying of the waves forward on the right side, thus giving the radial lines or sound-beams a curved form, (as shown by the lower lines *l i* and *i k*,) these being always perpendicular to the wave-faces. As this curvature or refraction is necessarily upward against the unequal wind and downward in the direction of the wind, an observer at *k* will hear with great distinctness the sound emanating from *i*, while an observer on the other side at *j* will hear nothing, by reason of the sound-beams being tilted above his head. By rising to an elevation, as at *l*, the observer will hear the sound as well against the wind as with it.

It is not a little surprising that an explanation of a well-marked and puzzling phenomenon, so elegant and so conclusive as that promulgated by Professor Stokes, should have remained for fifteen years unnoticed and unthought-of by the scientific world. When in 1865 Professor Henry discovered that "a sound moving against the wind, inaudible to the ear on the deck of a schooner, was heard by ascending to the mast-head, this remarkable fact at first suggested the idea that sound was more readily conveyed by the upper current of air than the lower." And this general idea seemed confirmed by the observation that with the upper and lower currents at variance the upper wind appeared to most favor the sound. Nor was it till early in 1872 that the full significance of all this became apparent on first learning of the explanation given by Professor Stokes. And yet during the same series of observations, Professor Henry discovered that the velocity of wind in the higher regions of the air was much greater than in the lower regions.

In like manner, Professor Reynolds having, in the spring of 1874, independently arrived at the same theory, and undertaken a series of experiments and observations in this direction, remarks: "I had just reached the point of making such tests, when I discovered that the same views had been propounded by Professor Stokes so long ago as 1857."—(*Proc. R. S.*, 1874.) Professor Reynolds made the decisive observations tha in the direction of the wind, the sound of a bell could be as well heard at a distance, with the head depressed as when standing; while against the wind, the sound at no great distance ceased to be heard, passing over the head, and could be regained in full force by elevation. It was found also that the elevation required to reach the lowest sound-beam increased with the distance.

If we suppose the wind near the surface of the earth (or at 6 feet above it) to be moving at the rate of six miles per hour, (one mile in 10 minutes, or 8.8 feet per second,) and at the elevation of 1,000 feet to be moving in the same direction with just double the velocity, then a vertical wave-front of sound in moving 4.7 seconds, or one mile, against such wind would be retarded 41 feet near the ground, and 82 feet at the height of 1,000 feet. This difference of 41 feet would so tilt the

wave-face backward that a line perpendicular to it would have an upward direction of about 2° 21′; or, an arc described with a radius of 24.39 miles would represent approximately the upward curvature of a horizontal sound-beam, whereby at the distance of a mile it would be lifted up about 108 feet. A wave-front of sound moving in the direction of the wind would, of course, be correspondingly accelerated above, and the beam bent downward in a similar arc.

A wind blowing along the face of an extended bluff or cliff, being retarded near the same by friction, would, in a similar manner, cause a sound originating near it to be laterally refracted toward the wall in the direction of the wind, and from it in the opposite direction.

When, from any cause, the upper wind should move more sluggishly than the lower wind, as sometimes occurs, the lines of refraction above indicated would be reversed, and we should have the exceptional case of sound being favored by an opposing wind, and *vice versa*.

This very simple principle of vental refraction has thus a wide practical range, and the variety of its applications is limited only by that of the actual differences in force and direction of the winds. In short, in the case of any divergence between the upper and lower currents, in whatever direction, there will be but two lines of no refraction. In all other directions, a positive or a negative resultant must to some degree disturb the direction of the acoustic ray.

In consequence of the slight internal friction (or "viscosity") of air, the shadow-line is not usually very sharply defined. Wave-impulses acting laterally on the adjacent air cause the sound to be feebly heard within the shadow-line; and the sound-beam is thus practically diffracted around an obstacle to an extent which is probably some function of its intensity or energy. The effect of this, in the case of a refracted beam, is to diminish somewhat its apparent curvature, and thus to render an uplifted sound sensible to a greater distance than it would be on a merely geometrical theory, or without such marginal diffusion.

From the same cause the following practical results follow: 1st. A continuous sound, as of a horn or steam-whistle, requires at a distance a short but appreciable interval (a second or more) to be heard with its full power; 2d. Hence, with adverse winds, sounds of single impulse, as those of bells and guns, are more refracted than continuous sounds, whose initial impulses are re-enforced by rhythmic successions, giving them greater persistence of force and direction; 3d. It is unnecessary to add that sounds under such circumstances (with beams of convex curvature) can be heard to a greater distance when originating from an elevation, and also when observed from an elevation; 4th. It is probable that sounds of high pitch are more refracted than medium tones and those of lower pitch.

3.—REFRACTION FROM INEQUALITY OF TEMPERATURE.

In 1874, Prof. Osborne Reynolds pointed out a third practical cause of acoustic refraction in the differences of temperature to which advancing

waves of sound are frequently subjected. He remarks: "Although barometric pressure does not affect the velocity of sound, yet, as is well known, the velocity of sound depends on the temperature, and every degree of temperature between 32° and 70° adds approximately one foot per second to the velocity of sound. This velocity also increases with the quantity of moisture in the air; but the quantity is at all times too small to produce an appreciable result. This vapor nevertheless plays an important part in the phenomena under consideration; for it gives to the air a much greater power of radiating and absorbing heat, and thus renders it much more susceptible of changes in the action of the sun. . . . It is a well-known fact that the temperature of the air diminishes as we proceed upward, and that it also contains less vapor. Hence it follows that, as a rule, the waves of sound must travel faster below than they do above, and thus be refracted or turned upward."—(*Proc. R. S.*, 1874.)

Professor Reynolds cites observations showing that on a calm clear day in July, 1873, while the sun was shining with great power, loud sounds which could be heard but two or three miles were heard several times this distance toward evening after the sun had become obscured with clouds. "Here we see that the very conditions which actually diminished the range of sound were precisely those which would cause the greatest lifting of the waves."

This furnishes a satisfactory explanation of the familiar fact that sounds heard during the day-time to comparatively short distances (especially in summer and with still air) are audible many times as far in the night. "Humboldt could hear the falls of Orinoco three times as loud by night as by day at a distance of one league; and he states that the same phenomenon has been observed near every waterfall in Europe." Humboldt also remarked that the heating effect of the sun was so great that "all distant objects had wavy undulating outlines, the optical effect of the *mirage*. Not a breath of air moved the dust-like sand. The sun stood in the zenith."—(*Views of Nature*, Bohn's ed., p. 200.) Dr. Gregory, in his experiments on sound, undertaken in 1824, observed that, on January 9, in the evening, with no wind stirring, "the sound of the same charge fired from the same musket was heard much more intensely on this clear frosty night than in the day-time of January 3, at the same distance, 3,600 feet."—(*Phil. Mag.*, 1824, lxiii, 404.)

Fig. 5 illustrates this effect of heated lower strata of air in tilting up the beams of sound in all directions. If we suppose the horizontal lines to mark spaces upward, of 100 yards each, into which the air is arranged by strata of diminishing temperatures of 3 degrees each, but increasing more rapidly near the surface, (75°, 70°, 67°, 64°,) then near the ground (at 75°) the horizontal sound beams will travel 5 feet per second (or 23.5 feet per mile) faster than at the line *n* of 70°, or the height of 300 feet; at this line, 3 feet per second (or 14 feet per mile)

faster than at the line *o* of 67°, or the height of 600 feet; and at this line the same quantity faster than at the line *p* of 64°, or the height of 900 feet. The result is that a vertical wave-front 900 feet deep would, at the distance of one mile, be advanced at its lower part more than 51 feet beyond its upper part, making an angle of about 3¼°; and the corresponding upward curvature of the lower sound-beams emanating from *m* (the versed sine of this arc) would amount to about 150 feet.

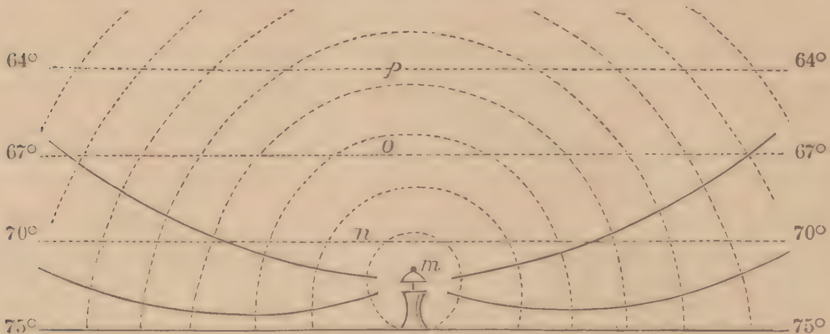

FIG. 5.—Thermal refraction.

If the temperature of the lower strata of air were found to increase only at half the rate above assumed, the lower sound-beams from *m* would be lifted one hundred and fifty feet in about two miles. If the differences of temperature were reduced to one-fourth, this amount of upward tilt would be reached in about four miles, &c.

From this it is apparent that temperature-refraction—the upward "dishing" of the lower sheet of sound by the overheating of the lower air—is not only a real phenomenon, but that in quantity it introduces a very considerable amount of disturbance in the direction of sound, and thus impairs seriously its audibility at any great distance on the surface of the earth.

In further illustration of the same principle, no less notable is the converse effect of an excess of *cooling* in the lower strata, occasionally noticed. Professor Reynolds, continuing his researches "On the refraction of sound," during the summer of 1875, found that, on the 19th of August, "after three weeks of cold and windy weather," the sea and the adjacent air being chilled considerably below the average or upper temperature, sound passing over the water reached the observers in a boat with such remarkable clearness that "guns, and on one occasion the barking of a dog, on the shore, eight miles distant, were distinctly heard, as were also the paddles of a steamer fifteen miles distant. The day was perfectly calm; there was no wind; the sky was quite clear, and the sun shining with great power." The significant circumstance is recorded that "all the time distant objects *loomed* considerably, *i. e.*, appeared lifted." In this case, "the diminution in the temperature of the air being downward, the sound instead of being

lifted as it usually is, was brought down, and thus intensified at the surface of the water, which, being perfectly smooth, was thus converted into a sort of whispering-gallery."—(*Proc. R. S.*, 1876.)

This action is illustrated by Fig. 6, in which the temperature of the air below the horizontal line *q r*, being gradually less toward the earth than above the line, the sound-waves originating at *s* are shortened lat-

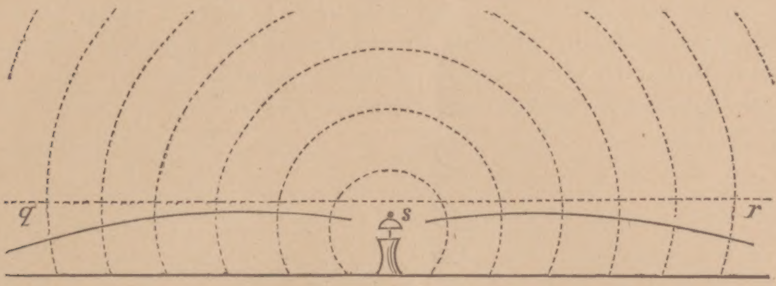

FIG. 6.—Refraction by cold.

erally (or in the direction of the lower rays) about one foot per second for each degree of refrigeration, and the sound-beams (always perpendicular to the waves) are thus gradually bent downward.

The remarkable distances to which sounds have sometimes been heard in Arctic regions receive here a satisfactory explanation. "Lieutenant Foster, in the third polar expedition of Captain Parry, found that he could hold a conversation with a man across the harbour of Port Bowen, a distance of 6,696 feet, or about a mile and a quarter."—(Sir J. Herschel, *Sound*, sect. 21.) The same author remarks of the polar regions: "In consequence of the intense cold of the icy surface, contrasted, as it sometimes is in summer, with the warmth of the air, the phenomena of atmospheric refraction are exaggerated in these regions in a most extraordinary manner; the forms of ice-bergs, rocks, etc., are seen drawn up in vertical altitude, and spread out at their apparent summits laterally, so as to present no resemblance to their real form."—(Sir J. Herschel, *Physical Geography*, sect. 98.) From which we learn that the optical deportment of the air may very often be accepted as an index of its acoustic condition.

In the play and interaction of these two great and prevalent modes of acoustic refraction—that resulting from co-existent differences of wind in varying directions and that from co-existent differences of temperature—whether re-enforcing or checking each other, or leaving a differential resultant, we have abundant opportunities to exercise the judgment and discrimination of the most diligent observers. Professor Reynolds noticed that on some clear nights in May and June, 1875, when a heavy dew indicated considerable refrigeration at the surface, "the sound could invariably be heard as far against a light wind as with it," showing that the upward refraction from wind was completely

counteracted by the downward refraction from diminution of temperature. This was observed not to be the case when the cloudiness of the night prevented terrestrial radiation and the deposition of dew.—(*Proc. R. S.*, 1876.)

It has thus been shown in the course of this discussion, that while the refraction of sound as illustrated by gas lenses, still retains its original interest as a striking class-experiment, the far more important examples of acoustic refraction constantly presented by the infinitely varied conditions of differing air-currents and of differing air-temperatures, have until very recently, attracted no attention, and their practical significance has been strangely overlooked.